

MULTIPLE-BEAM ANTENNA WITH PHOTONIC BANDGAP MATERIAL

The invention relates to a multiple-beam antenna comprising:

- 5 - a photonic bandgap material for filtering electromagnetic waves spacewise and frequencywise, this photonic bandgap material having at least one bandgap and forming an outer surface radiating in transmit and/or receive mode,
- 10 - at least one periodicity defect of the photonic bandgap material so as to produce at least one narrow bandwidth within said at least one bandgap of this photonic bandgap material, and
- 15 - an excitation device for transmitting and/or receiving electromagnetic waves within said at least one narrow bandwidth produced by said at least one defect.

Multiple-beam antennas are very widely used in space applications and in particular in geostationary satellites for transmitting to the Earth's surface and/or receiving information from the Earth's surface. For this, they include a number of radiating elements each generating a beam of electromagnetic waves spaced apart from the other beams. These radiating elements are, for example, placed near the focal point of a parabola forming an electromagnetic wave beam reflector, the parabola and the multiple-beam antenna being housed in a geostationary satellite. The parabola is for directing each beam onto a corresponding area of the Earth's surface. Each area of the Earth's surface lit by a beam from the multiple-beam antenna is commonly called a coverage area. Thus, each coverage area corresponds to a radiating element.

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Currently, the radiating elements used are known as "horns" and the multiple-beam antenna equipped with such horns is known as horn antenna. Each horn produces a roughly circular radiating spot forming the base of a

- 2 -

conical beam radiated in transmit and/or in receive mode. These horns are placed alongside each other so as to keep the radiating spots as close as possible to each other.

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Figure 1A diagrammatically represents a multiple-beam horn antenna seen from the front, in which seven squares F1 to F7 indicate the footprint of seven horns placed contiguous to each other. Seven circles S1 to 10 S7, each inscribed in one of the squares F1 to F7, represent the radiating spots produced by the corresponding horns. The antenna of figure 1A is placed at the focal point of a parabola of a geostationary satellite for transmitting information to France.

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Figure 1B represents the -3 dB coverage areas C1 to C7, each corresponding to a radiating spot of the antenna of figure 1A. The center of each circle corresponds to a point on the Earth's surface where the received power 20 is maximum. The circumference of each circle delimits an area inside which the received power on the Earth's surface is greater than half of the maximum received power at the center of the circle. Although the radiating spots S1 to S7 are practically contiguous, 25 the latter produce -3 dB coverage areas that are separate from each other. The regions situated between the -3 dB coverage areas are, here, called reception gaps. Each reception gap therefore corresponds to a region of the Earth's surface where the received power 30 is less than half of the maximum received power. In these reception gaps, the received power may be inadequate for a receiver on the ground to be able to operate correctly.

35 To overcome this reception gap problem, it has been proposed to make the radiating spots of the multiple-beam antenna overlap. A partial front view of such a multiple-beam antenna with a number of overlapping radiating spots is illustrated in figure 2A. In this

figure, only two radiating spots SR1 and SR2 are represented. Each radiating spot is produced from seven radiation sources that are independent of and separate from each other. The radiating spot SR1 is formed from 5 the radiation sources SdR1 to SdR7 placed contiguous to each other. A radiating spot SR2 is produced from the radiation sources SdR1, SdR2, SdR3 and SdR7 and radiation sources SdR8 to SdR10. The radiation sources SdR1 to SdR7 are suited to working at a first working 10 frequency to produce a first beam of electromagnetic waves roughly uniform at this first frequency. The radiation sources SdR1 to SdR3 and SdR7 to SdR10 are suited to working at a second working frequency to produce a second beam of electromagnetic waves roughly 15 uniform at this second working frequency. Thus, the radiation sources SdR1 to SdR3 and SdR7 are designed to work simultaneously at the first and second working frequencies. The first and second working frequencies are different from each other so as to limit 20 interference between the first and second beams produced.

Thus, in such a multiple-beam antenna, radiation sources, such as the radiation sources SdR1 to SdR3 are 25 used to create both the radiating spot SR1 and the radiating spot SR2, which produces an overlap of these two radiating spots SR1 and SR2. An illustration of the placement of the -3 dB coverage areas created by a multiple-beam antenna having overlapping radiating 30 spots is represented in figure 2B. Such an antenna considerably reduces the reception gaps, and can even eliminate them. However, partly because of the fact that a radiating spot is formed from a number of radiation sources that are independent of and separate 35 from each other, at least some of which are also used for other radiating spots, this multiple-beam antenna is more complicated to control than the conventional horn antennas.

The invention seeks to overcome this problem by proposing a simpler multiple-beam antenna with overlapping radiating spots.

5 Its object is therefore an antenna as defined above, characterized:

- in that the excitation device is designed to work simultaneously at least about a first and a second separate working frequencies,

10 - in that the excitation device includes a first and a second excitation elements, separate from and independent of each other, each designed to transmit and/or receive electromagnetic waves, the first excitation element being designed to work at the first working frequency and the second excitation element being designed to work at the second working frequency,

- in that the or each periodicity defect of the photonic bandgap material forms a leaky resonating cavity presenting a constant height in a direction orthogonal to said radiating outer surface, and predefined lateral dimensions parallel to said radiating outer surface,

20 - in that the first and the second working frequencies are designed to excite the same resonance mode of a leaky resonant cavity, this resonance mode being established identically regardless of the lateral dimensions of the cavity, so as to create on said outer surface respectively a first and a second radiating spots, each of these radiating spots representing the origin of a beam of electromagnetic waves radiated in transmit and/or receive mode by the antenna,

25 - in that each of the radiating spots has a geometric center, the position of which depends on the position of the excitation element producing it and the area of which is greater than that of the radiating element producing it, and

- in that the first and the second excitation elements are placed relative to each other such that the first and the second radiating spots are positioned on the

outer surface of the photonic bandgap material alongside each other and partially overlapping.

In the multiple-beam antenna described above, each 5 excitation element produces a single radiating spot forming the base or cross section at the origin of a beam of electromagnetic waves. Thus, from this point of view, this antenna is comparable to conventional horn antennas in which a horn produces a single radiating 10 spot. The control of this antenna is therefore similar to that of a conventional horn antenna. Furthermore, the excitation elements are placed so as to overlap the radiating spots. This antenna therefore has the 15 advantages of a multiple-beam antenna with overlapping radiating spots without the complexity of the control of the excitation elements having been increased compared with that of the multiple-beam horn antennas.

According to other features of a multiple-beam antenna 20 according to the invention:

- each radiating spot is roughly circular, the geometric center corresponding to a maximum transmitted and/or received power and the periphery corresponding to a maximum transmitted and/or received power equal to 25 a fraction of the maximum transmitted and/or received power at its center, and the distance, in a plane parallel to the outer surface, separating the geometric centers of the two excitation elements, is strictly less than the radius of the radiating spot produced by 30 the first excitation element added to the radius of the radiating spot produced by the second excitation element,
- the geometric center of each radiating spot is placed on the line perpendicular to said radiating outer 35 surface and passing through the geometric center of the excitation element producing it,
- the first and the second excitation elements are placed inside one and the same cavity,

- the first and the second working frequencies are situated within the same narrow bandwidth created by this same cavity,
- 5 - the first and the second excitation elements are each placed inside separate resonating cavities, and the first and the second working frequencies are designed each to excite a resonance mode independent of the lateral dimensions of their respective cavities,
- 10 - an electromagnetic radiation reflector plane associated with the photonic bandgap material, this reflector plane being distorted so as to form said separate cavities,
- the or each cavity is of parallelepipedal shape,
- 15 - the device for focusing the electromagnetic waves comprises a reflector in half-cylinder shape, and the photonic bandgap material of the antenna has a convex surface corresponding to the half-cylinder-shaped surface of the reflector.

20 The invention also relates to a system for transmitting and/or receiving electromagnetic waves comprising:

- a device for focusing the electromagnetic waves transmitted and/or received by the system on a focal point, and
- 25 - a transmitter and/or receiver of electromagnetic waves placed roughly at the focal point so as to transmit and/or receive said electromagnetic waves, characterized in that it comprises an antenna according to the invention, the outer radiating surface of which
- 30 is placed roughly on the focal point so as to form said transmitter and/or receiver of electromagnetic waves.

According to other features of the system according to the invention:

- 35 - the device for focusing the electromagnetic waves is a parabolic reflector,
- the device for focusing the electromagnetic waves is an electromagnetic lens.

The invention will be better understood on reading the description that follows, given purely by way of example, and made with reference to the drawings, in which:

5 - figures 1A, 1B, 2A and 2B represent known multiple-beam antennas and the resulting coverage areas;

- figure 3 is a perspective view of a multiple-beam antenna according to the invention;

10 - figure 4 is a graph representing the transmission factor of the antenna of figure 3;

- figure 5 is a graph representing the radiation pattern of the antenna of figure 3;

15 - figure 6 is a cross-sectional diagrammatic illustration of a system for transmitting/receiving electromagnetic waves equipped with the antenna of figure 3;

- figure 7 represents a second embodiment of a multiple-beam antenna according to the invention;

20 - figure 8 represents the transmission factor of the antenna of figure 7;

- figure 9 represents a third embodiment of a multiple-beam antenna according to the invention; and

- figure 10 is an illustration of a half-cylindrical antenna according to the invention.

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Figure 3 represents a multiple-beam antenna 4. This antenna 4 is formed of a photonic bandgap material 20 associated with a metallic plane 22 reflecting electromagnetic waves.

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Photonic bandgap materials are known and the design of a photonic bandgap material such as the material 20 is, for example, described in patent application FR 99 14521. Thus, only the specific features of the antenna 4 compared to this state of the art are described here in detail.

It should be remembered that a photonic bandgap material is a material that has the property of

absorbing certain frequency ranges, that is, preventing any transmission in said abovementioned frequency ranges. These frequency ranges form what is here called a bandgap.

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A bandgap B of the material 20 is illustrated in figure 4. This figure 4 shows a curve representing the variations of the transmission factor expressed in decibels versus the frequency of the electromagnetic 10 wave transmitted or received. This transmission factor is representative of the power transmitted on one side of the photonic bandgap material compared to the power received on the other side. In the case of the material 20, the bandgap B or the absorption band B extends 15 roughly from 7 GHz to 17 GHz.

The position and the width of this bandgap B depend only on the properties and the characteristics of the photonic bandgap material.

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The photonic bandgap material is normally made up of a periodic arrangement of dielectrics of variable permittivity and/or permeability. Here, the material 20 is formed from two plates 30, 32 made of a first 25 magnetic material such as aluminum and two plates 34 and 36 made of a second magnetic material such as air. The plate 34 is sandwiched between the plates 30 and 32, while the plate 36 is sandwiched between the plate 32 and the reflecting plane 22. The plate 30 is 30 positioned at one end of this stack of plates. It has an outer surface 38 opposite to its surface in contact with the plate 34. This surface 38 forms a radiating surface in transmit and/or receive mode.

35 In a known manner, the introduction of a break in this geometric and/or radiofrequency periodicity, such a break also being called a defect, can generate an absorption defect and therefore create a narrow bandwidth within the bandgap of the photonic bandgap

material. The material is, in these conditions, called defective photonic bandgap material.

5 Here, a break in the geometric periodicity is created by choosing the height or thickness H of the plate 36 to be greater than that of the plate 34. In a known manner, and to create a narrow bandwidth E (figure 4) roughly in the middle of the bandwidth B , this height H is defined by the following relation:

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$$H = 0.5 \times \lambda / \sqrt{\epsilon_r \times \mu_r}$$

in which:

15 - λ is the wavelength corresponding to the median frequency f_m of the bandwidth E ,

- ϵ_r is the relative permittivity of the air, and
- μ_r is the relative permeability of the air.

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Here, the median frequency f_m is roughly equal to 1.2 GHz.

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The plate 36 forms a leaky parallelepipedal resonant cavity, the height H of which is constant and the lateral dimensions of which are defined by the lateral dimensions of the photonic bandgap material 20 and of the reflector 22. These plates 30 and 32, and the reflecting plane 22, are rectangular and of identical lateral dimensions. Here, these lateral dimensions are chosen in such a way as to be several times larger than 30 the radius R defined by the following empirical formula:

$$G_{dB} \geq 20 \log \frac{\pi \Phi}{\lambda} - 2.5. \quad (1)$$

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in which:

- G_{dB} is the gain in decibels required for the antenna,
- $\Phi = 2 \pi R$,

- 10 -

- λ is the wavelength corresponding to the median frequency f_m .

5 As an example, for a gain of 20 dB, the radius R is roughly equal to 2.15λ .

10 In a known manner, such a parallelepipedal resonant cavity offers a number of families of resonance frequencies. Each family of resonance frequencies is formed by a fundamental frequency and its harmonics or integer multiples of the fundamental frequency. Each 15 resonance frequency of one and the same family excites the same resonance mode of the cavity. These resonance modes are known by the resonance mode terms TM_0 , TM_1 , TM_2 , ..., TM_i , etc. These resonance modes are described in greater detail in the document by F. Cardiol, "Electromagnétisme, traité d'Electricité, d'Electronique et d'Electrotechnique", Ed. Dunod, 1987.

20 It should be remembered here that the resonance mode TM_0 is liable to be excited by a range of excitation frequencies adjacent to a fundamental frequency f_{m0} . Similarly, each mode TM_i is liable to be excited by a 25 range of excitation frequencies adjacent to a fundamental frequency f_{mi} . Each resonance mode corresponds to a radiation pattern of the particular antenna and to a radiating spot in transmit and/or receive mode formed on the outer surface 38. The radiating spot is in this case the area of the outer 30 surface 38 containing all of the spots where the power radiated in transmit and/or receive mode is greater than or equal to half the maximum power radiated from this outer surface by the antenna 4. Each radiating spot has a geometric center corresponding to the point 35 where the radiated power is roughly equal to the maximum radiated power.

In the case of the resonance mode TM_0 , this radiating spot is inscribed in a circle, the diameter ϕ of which

- 11 -

is given by the formula (1). For the resonance mode TM_0 , the radiation pattern is in this case strongly directional along a direction perpendicular to the outer surface 38 and passing through the geometric 5 center of the radiating spot. The radiation pattern corresponding to the resonance mode TM_0 is illustrated in figure 5.

10 The frequencies f_{mi} are placed inside the narrow bandwidth E.

Finally, four excitation elements 40 to 43 are placed alongside each other inside the cavity 36 on the reflecting plane 22. In the example described here, the 15 geometric centers of these excitation elements are placed at the four corners of a lozenge, the dimensions of the sides of which are strictly less than $2R$.

20 Each of these excitation elements is designed to transmit and/or receive an electromagnetic wave at a working frequency f_{Ti} different from that of the other excitation elements. Here, the frequency f_{Ti} of each excitation element is adjacent to f_m so as to excite the resonance mode TM_0 of the cavity 36. These 25 excitation elements 40 to 43 are connected to a conventional generator/receiver 45 of electrical signals to be transformed by each excitation element into an electromagnetic wave and vice versa.

30 These excitation elements are, for example, made of a radiating dipole, a radiating slot, a plate probe or a radiating patch. The lateral footprint of each radiating element, that is, in a plane parallel to the outer surface 38, is strictly less than the area of the 35 radiating spot that it produces.

Figure 6 illustrates a typical application of the antenna 4. Figure 6 represents a system 60 for transmitting and/or receiving electromagnetic waves

suitable for a geostationary satellite. This system 60 includes a parabola 62 forming an electromagnetic wave beam reflector and the antenna 4 placed at the focal point of this parabola 62. The electromagnetic wave 5 beams transmitted or received by the outer surface 38 of the antenna 4 are represented in this figure by lines 64.

10 The operation of the antenna of figure 3 will now be described in the particular case of the system of figure 6.

In transmit mode, the excitation element 40, activated by the generator/receiver 45, transmits an 15 electromagnetic wave at a working frequency f_{T0} and excites the resonance mode TM_0 of the cavity 36. The other radiating elements 41 to 43 are, for example, simultaneously activated by the generator/receiver 45 and do the same respectively at the working frequencies 20 f_{T1} , f_{T2} and f_{T3} .

It has been discovered that, for the resonance mode TM_0 , the radiating spot and the corresponding radiation pattern are independent of the lateral dimensions of 25 the cavity 36. In practice, the resonance mode TM_0 depends only on the thickness and the nature of the materials of each of the plates 30 to 36 and is established independently of the lateral dimensions of the cavity 36 when the latter are several times greater 30 than the radius R defined previously. Thus, several resonance modes TM_0 can be created simultaneously alongside one another and therefore simultaneously generate several radiating spots disposed alongside one another. This is what happens when the excitation 35 elements 40 to 43 excite, each at different points in space, the same resonance mode. Consequently, the excitation by the excitation element 40 of the resonance mode TM_0 is reflected in the appearance of a roughly circular radiating spot 46, the geometric

center of which is situated in a line vertical to the geometric center of the element 40. Similarly, the excitation by the elements 41 to 43 of the resonance mode TM_0 is reflected in the appearance, in the line 5 vertical to the geometric center of each of these elements, respectively of radiating spots 47 to 49. Since the geometric center of the element 40 is at a distance strictly less than $2R$ from the geometric center of the elements 41 and 43, the radiating spot 46 10 partly overlaps the radiating spots 47 and 49 respectively corresponding to the radiating elements 41 and 43. For the same reasons, the radiating spot 49 partly overlaps the radiating spots 46 and 48, the radiating spot 48 partly overlaps the radiating spots 15 49 and 47 and the radiating spot 47 partly overlaps the radiating spots 46 and 48.

Each radiating spot corresponds to the base or cross section at the origin of an electromagnetic wave beam 20 radiated to the parabola 62 and reflected by this parabola 62 toward the Earth's surface. Thus, in a manner similar to the known multiple-beam antennas with overlapping radiating spots, the coverage areas on the Earth's surface corresponding to each of the 25 transmitted beams are close to each other, or even overlap, so as to eliminate or reduce the reception gaps.

In receive mode, in a manner similar to what has been 30 described in transmit mode, each radiating spot of the outer surface 38 corresponds to a coverage area on the Earth's surface. Thus, for example, if an electromagnetic wave is transmitted from the coverage area corresponding to the radiating spot 46, the latter 35 is received in the area corresponding to the spot 46 after having been reflected by the parabola 62. If the wave received is at a frequency included in the narrowband bandwidth E , it is not absorbed by the photonic bandgap material 20 and it is received by the

excitation element 40. Each electromagnetic wave received by an excitation element is transmitted in the form of an electrical signal to the generator/receiver 45.

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Figure 7 represents an antenna 70 made of a photonic bandgap material 72 and an electromagnetic wave reflector 74 and figure 8 shows the trend of the transmission factor of this antenna versus frequency.

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The photonic bandgap material 72 is, for example, the same as the photonic bandgap material 20 and presents the same bandgap B (figure 8). The plates forming this photonic bandgap material already described with 15 respect to figure 3 are given the same numeric references.

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The reflector 74 is formed, for example, from the reflecting plane 22 distorted so as to divide the cavity 36 into two resonating cavities 76 and 78 of different heights. The constant height H_1 of the cavity 76 is determined in such a way as to place, within the bandgap B, a narrow bandwidth E_1 (figure 8), for example, about the 10 GHz frequency. Similarly, the 25 height H_2 of the resonating cavity 78 is determined to place, within the same bandgap B, a narrow bandwidth E_2 (figure 8), for example centered about 14 GHz. The reflector 74 is in this case made up of two reflecting half-planes 80 and 82 staggered and electrically linked 30 to each other. The reflecting half-plane 80 is parallel to the plate 32 and spaced from it by the height H_1 . The half-plane 82 is parallel to the plate 32 and spaced from the latter by the constant height H_2 .

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Finally, an excitation element 84 is positioned in the cavity 76 and an excitation element 86 is positioned in the cavity 78. These excitation elements 84, 86 are, for example, identical to the excitation elements 40 to 43, apart from the fact that the excitation element 84

is specifically for exciting the resonance mode TM_0 of the cavity 76, whereas the excitation element 86 is specifically for exciting the resonance mode TM_0 of the cavity 78.

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In this embodiment, the horizontal distance, that is, the distance parallel to the plate 32, separating the geometric center of the excitation elements 84 and 86, is strictly less than the sum of the radii of two 10 radiating spots respectively produced by the elements 84 and 86.

The operation of this antenna 70 is identical to that 15 of the antenna of figure 3. However, in this embodiment, the working frequencies of the excitation elements 84 and 86 are situated in respective narrow bandwidths E_1 , E_2 . Thus, unlike the antenna 4 of figure 3, the working frequencies of each of these excitation elements are separated from each other by a wide 20 frequency interval, for example, in this case, 4 GHz. In this embodiment, the positions of the bandwidths E_1 , E_2 are chosen so as to be able to use imposed working frequencies.

25 Figure 9 represents a multiple-beam antenna 100. This antenna 100 is similar to the antenna 4 apart from the fact that the single-defect photonic bandgap material 20 of the radiating device 4 is replaced by a photonic bandgap material 102 with several defects. In figure 7, 30 the elements already described with regard to figure 4 are given the same numeric references.

The antenna 100 is represented in cross-section through 35 a cutting plane perpendicular to the reflecting plane 22 and passing through the excitation elements 41 and 43.

The photonic bandgap material 102 has two successive groupings 104 and 106 of plates made of a first

5 dielectric material. The groupings 104 and 106 are stacked in the direction perpendicular to the reflecting plane 22. Each grouping 104, 106 is formed, by way of nonlimiting example, respectively by two plates 110, 112 and 114, 116 parallel to the reflecting plane 22. Each plate of a grouping has the same thickness as the other plates of this same grouping. In 10 the case of the grouping 106, each plate has a thickness $e_2 = \lambda/2$ in which λ denotes the wavelength of the median frequency of the narrow band created by the defects of the photonic bandgap material.

Each plate of the grouping 104 has a thickness $e_1 = \lambda/4$.

15 The calculation of these thicknesses e_1 and e_2 follows from the teaching disclosed in French patent 99 14521 (2 801 428).

20 Between each plate of the defective photonic bandgap material 102 is sandwiched a plate made of a second dielectric material, such as air. The thickness of these plates separating the plates 110, 112, 114 and 116 is equal to $\lambda/4$.

25 The first plate 116 is positioned facing the reflecting plane 22 and separated from this plane by a plate of a second dielectric material of thickness $\lambda/2$ so as to form a leaky parallelepipedal resonating cavity. Preferably, the thickness e_1 of the plates of 30 dielectric material of each consecutive group of plates of dielectric material, is in geometrical progression of ratio q in the direction of the successive groupings 104, 106.

35 Furthermore, in the embodiment described here, by way of nonlimiting example, the number of stacked groupings is equal to two so as not to overload the drawing, and the geometrical progression ratio is also equal to 2. These values are not limiting.

This stacking of groupings of photonic bandgap material having characteristics of different magnetic permeability, dielectric permittivity and thickness ϵ_i 5 increases the width of the narrow bandwidth created within the same bandgap of the photonic bandgap material. Thus, the working frequencies of the radiating elements 40 to 43 are chosen to be further apart from each other than in the embodiment of 10 figure 3.

The operation of this radiating device 100 derives directly from that of the antenna 4.

15 As a variant, the parabola 62 is replaced by an electromagnetic lens.

The radiating devices described hitherto are made of flat structures. However, as a variant, the surface of 20 these various elements is adapted to the shape of the parabola or of the device for focusing the electromagnetic wave beams. For example, figure 10 represents an antenna 200 equipped with a device 202 for focusing the electromagnetic wave beams on an 25 antenna 204. The device 202 is, for example, a metallic reflector of half-cylindrical shape. The antenna 204 is placed at the focal point of this device 202. The antenna 204 is similar to the antenna of figure 3, apart from the fact that the reflecting plane, and the 30 plates of the defective photonic bandgap material, each have a convex surface corresponding to the concave surface of the half-cylinder.

As a variant, the radiation transmitted or received by 35 each excitation element is polarized in a direction different to that used by the adjacent excitation elements. Advantageously, the polarization of each excitation element is perpendicular to that used by the adjacent excitation elements. Thus, the interference

- 18 -

and couplings between adjacent excitation elements are limited.

As a variant, one and the same excitation element is
5 adapted to operate successively or simultaneously at
several different working frequencies. Such an element
can be used to create a coverage area in which, for
example, transmission and reception take place at
different wavelengths. Such an excitation element is
10 also suitable for frequency switching.